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A NEW RADAR CONCEPT FOR TOP ATTACK WEAPON SYSTEMS

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Recent advances in solid state technology, especially in the millimeter wavelength portion of the spectrum, have made the concept of self-contained munitions a reality. Special self-contained armor defeating munitions usually attack from above where the target is larger and more vulnerable. The sensor elements, millimeter wavelength radar, radiometry, or infrared detectors must operate in a high clutter environment. The sensors, operational as hybrid units or individually, must be able to detect select targets in their natural backgrounds.

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This report presents details of design and measured data from a unique radar sensor developed at BRL for use with self-contained munitions now under development at ARRADCOM.

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I. INTRODUCTION

Since the early 1970's, the BRL has been involved in the testing of sensors for top-attack weapons systems. The earliest work was performed with the millimetre-wave TGSM which had active and passive sensing modes at 35 GHz. Other programs for which measurements were made were SADARM, STAFF, CYCLOPS, and WAM. The majority of the effort involved millimetre wave radiometry, although measurements of targets and clutter were made with radars and infrared radiometers.

This report describes the most recent series of measurements for top-attack systems using a cross-polarized millmetre-wave radar designed and built by the BRL.

In the tactical application, SADARM submunitions would be delivered by artillery, rockets, or guided bombs over a predesignated area of enemy armored vehicles or emplaced artillery. The submunitions would deploy parachutes for stabilization of drop velocity and rotation rate. The parachute dynamics cause the sensor, which is suspended at 30 degrees inclination, to scan a spiral pattern on the ground as it descends. The total search area for each submunition is enclosed in a 150 meter diameter circle on the ground. When the sensor beam intercepts a worthy target a coaligned self-forging fragment warhead is detonated.

The STAFF weapon system concept is a tube launched projectile that is fired over an armored target. The projectile spins at approximately 100 revolutions per second as it approaches the target. The STAFF sensor must accurately measure the projectile spin rate, detect the target, and fire a self-forging fragment warhead at the center of the target.

The millimeter wavelength radiometer is ideally suited to both these weapon system applications. Its ability to detect metal targets and direct fire to the center of the target was proven in both the SADARM and STAFF demonstration programs. However, the wide RF bandwidth and high sensitivity of the receiver make it susceptible to barrage jamming. A low powered RF source mounted on each target could interfere with the operation of this sensor.

During the early testing phase of the radiometric sensor, it was apparent that an additional sensor would be required to counter possible countermeasure threats. This additional sensor would have to be less susceptible to all types of countermeasure and still be able to detect valid targets and direct the munition to a vulnerable part of the target. A simple FM-CW radar could be fabricated with the same component parts as the radiometric sensor. This radar could operate at any frequency within the millimetre wavelength spectrum, including the regions of high atmospheric attenuation. The operational bandwidth would be narrow and the receiver sensitivity would be reduced.

In FY 79 and continuing into FY82, a series of radar sensors was fabricated and tested at BRL. A portable 30 meter tower and a helicopter were used to measure targets and background. This program has led to the development of a brassboard system which incorporates new radar concepts for receiver noise and background clutter reduction.

II. THE BRL BI-FREQUENCY CROSS-POLARIZED RADAR

Table I delineates the characteristics of the sensor being tested by the BRL. It is a dual mode sensor in that in addition to having an active channel of operation, a parallel passive channel operates. The passive channel is identical in operation to the passive system recently used in the successful SADARM demonstration program. It is used for comparison of the active and passive target detection and pointing and for comparison of the false target densities. It operates at a different IF frequency from the radar portion to prevent interference. The passive channel will not be discussed in detail.

Table 1. Bi-Frequency Homodyne Radar Characteristics

Antenna		
Type	Scalar-feed, Horn lens	
Polarization	Transmission	Vertical
	Reception	Horizontal
Diameter		.152 metres
Beam width (one-way)		4.7 degrees
Sidelobe level	Co-polarized	-27 dB
	Cross-polarized	-32 dB
Polarization Isolation		-32 dB
Loss		
Transmission		2 dB
Reception		2 dB
GUNN VCO		
Power to Circulator		19.4 dBm
Power to Mixer		9.4 dBm
Frequency		34-35.2 GHz
Tuning Rate		1 GHz/50 nsec
Power Variation		3 dB
Modulation		Squarewave
Modulation Step		400 MHz
Total RF Bandwidth		250 MHz
Modulation Rate		400 KHz
Frequency Diversity Rate		30 KHz
Receiver		
Noise Figure	(without modulation)	5 dB DSB
Noise Figure	(with modulation)	6.5 dB DSB
I.F. Bandwidth	Radar	100 MHz
	Radiometer	500 MHz
AGC Range		60 dB
Video Bandwidth	Radar	20 MHz
	Radiometer	5 KHz

The active system is basically a homodyne radar but with a few unique characteristics. As is demonstrated with the data presented later, the utilization of orthogonal polarizations on transmission and reception increases the signal-to-clutter ratio over that obtained for a normal co-polarized radar. The antenna used for the BRL sensor is a scalar-feed horn lens with circular wave guide input. In order to obtain the orthogonal

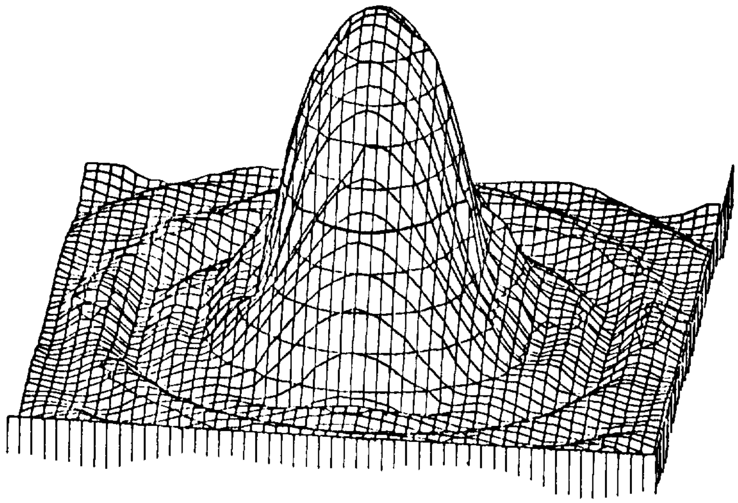

Figure 1. Co-Polarization Antenna Pattern (Parabolic Reflector)

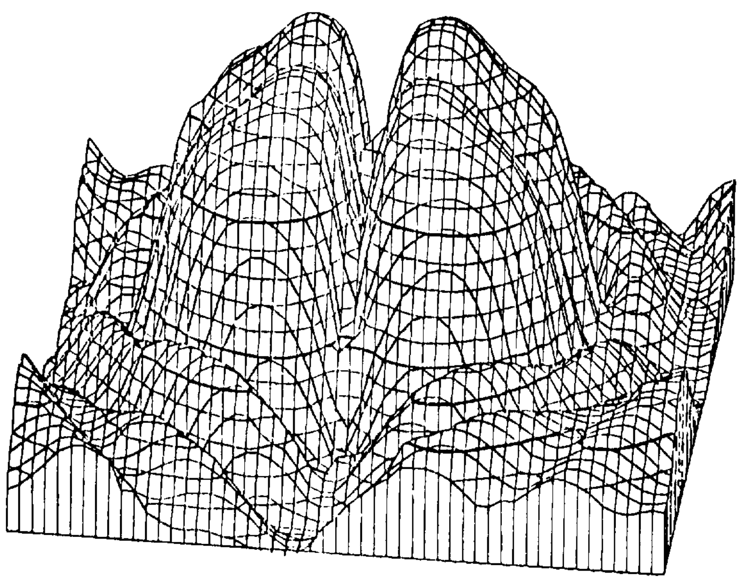

Figure 2. Cross-Polarization Antenna Pattern (Parabolic Reflector)

polarizations for transmission and reception, a faraday rotator is positioned between the antenna input and the radar front-end. The rotator is matched to the antenna through circular waveguide and to the front-end with a rectangular to circular transition. The transmitted signal polarization is rotated by the ferrite device 45 degrees clockwise and is radiated by the antenna. Any signal intercepted by the antenna is rotated 45 degrees counterclockwise. If the intercepted signal is the same polarization as transmitted, it will be rotated perpendicular to the waveguide polarization of the front-end. A vane in the rectangular to circular transition helps to dissipate this signal so that the receiver will reject it by about 30dB. Any signal received with orthogonal polarization will be rotated into the guide and will be received with little loss. This device was used, instead of an orthomode transducer, to test a technique for providing orthogonal polarizations with a self-mixing GUNN front-end which has a signal input/output port.

It has been found that when a circular aperture is used in an antenna, the intercardinal sidelobes may have a significant cross-polarized component. This is due to the rotation of the electric field of the illumination pattern by those portions of the aperture which are not parallel or perpendicular to the nominal polarization. Figure 1 is the one-way antenna pattern of a parabolic reflector antenna when the antenna receives vertical polarization and the transmitter of the pattern measuring range transmits vertical polarization. The azimuthal and elevation increments are .5 degree. The light contours are 3 dB levels. Figure 2 is the same antenna but with the transmitter radiating horizontal polarization. It can be seen that even though the co-polarized sidelobes are low in Figure 1, the cross-polarized sidelobes are dominant in Figure 2. If a normal two-axis antenna pattern were made with the configuration of Figure 2, the only effect noticed would be the loss in the main beam gain. The four intercardinal lobes that do appear are at 45 degree angles to nominal polarization axis and are approximately 30 dB greater in amplitude than the on boresight signal. If this antenna were used in a cross-polarized radar which scans over a trihedral, the signal could appear as two peaks with negligible signal when the nominal boresight is centered over the reflector. Two methods of alleviating this problem are apparent: either use an antenna with a rectangular effective aperture or increase the taper of the aperture illumination function. The scalar-feed horn lens does the latter.

The patterns obtained for the orthogonally polarized antenna being used in the radar are shown in Figures 3 through 6. Figures 3 and 4 are with the instrumentation antenna co-polarized with antenna under test. The sidelobes in all directions are down at least 27 dB from the main beam. In Figures 5 and 6 it can be seen that the intercardinal sidelobes are no higher than the cross-polarized main beam as required. The spike on one corner is a calibration point with amplitude equal to the co-polarized main beam level. The peak co-polarized received signal is at least 32 dB down across the pattern, which indicates that the radar would reject co-polarized signals by 32 dB.

In order to obtain range information with a minimum of components, a new modulation technique was developed.

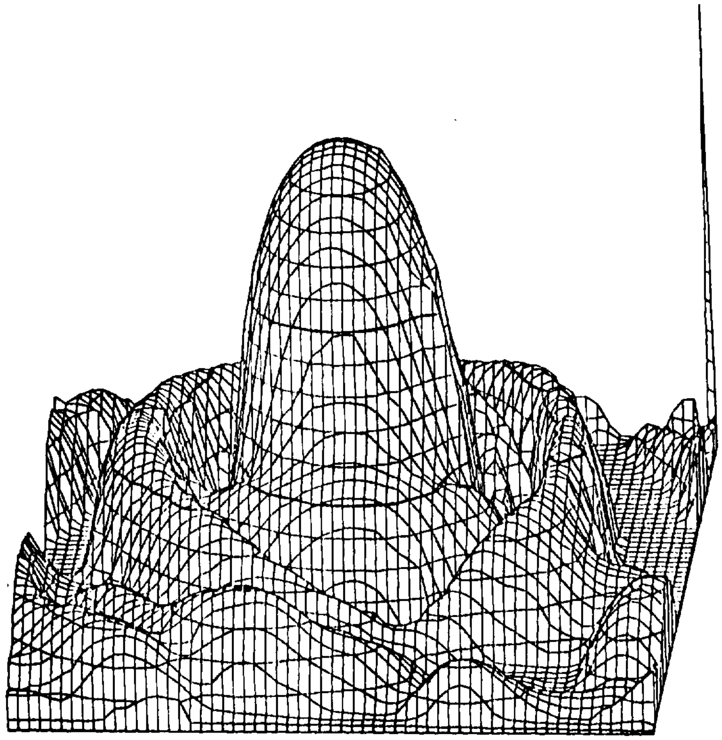

Figure 3. Co-Polarization Antenna Pattern (Scalar-Feed Horn Lens)

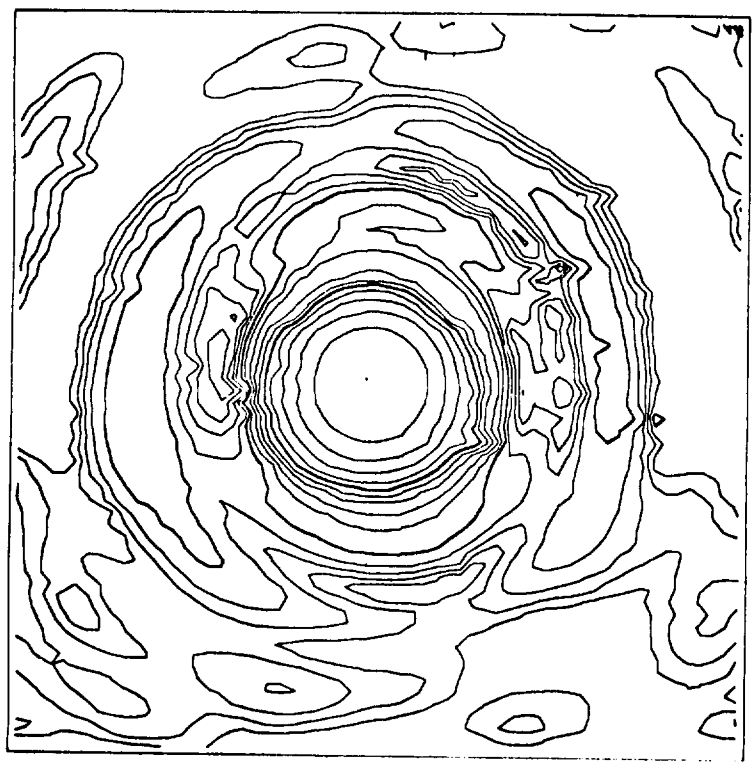

Figure 4. Co-Polarization Contour Plot (Scalar-Feed Horn Lens)

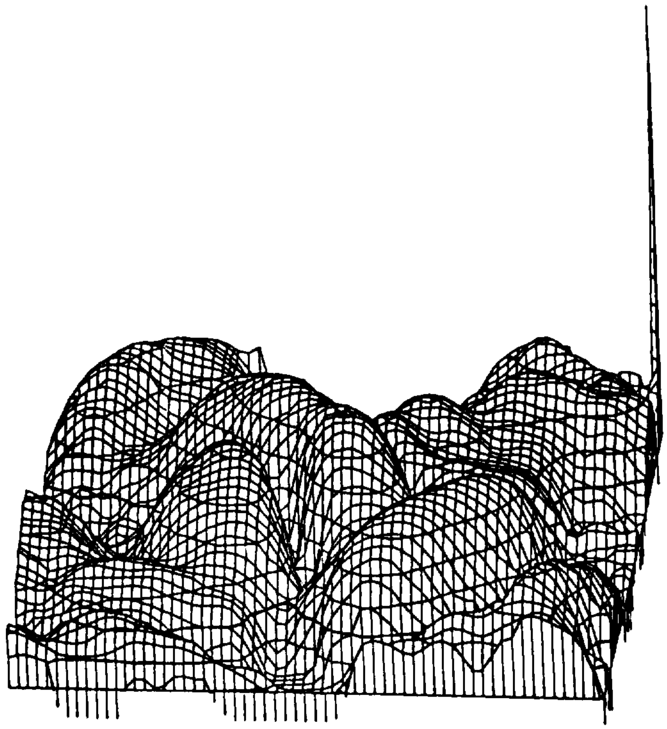

Figure 5. Cross-Polarization Antenna Pattern (Scalar-Feed Horn Lens)

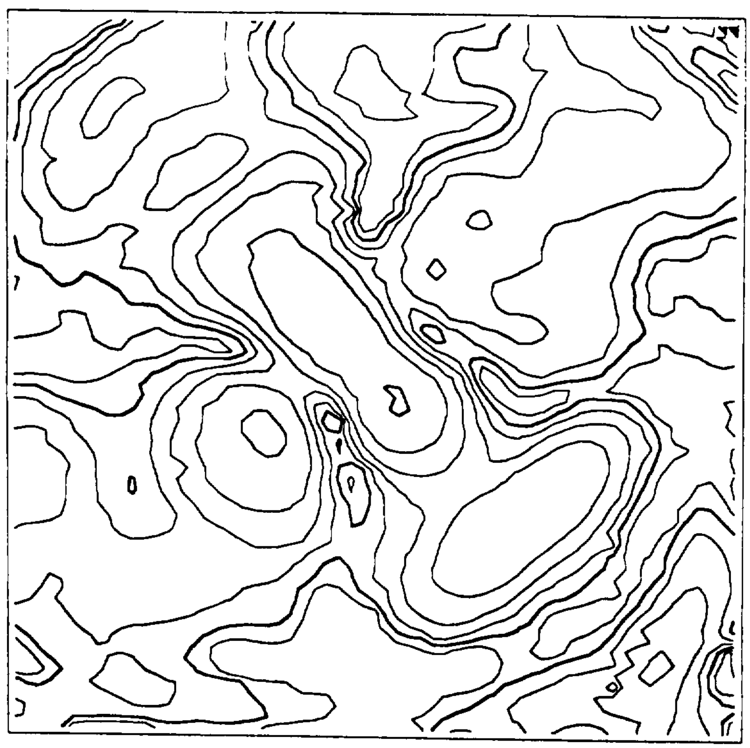

Figure 6. Cross-Polarization Contour Plot (Scalar-Feed Horn Lens)

The basic equation[1] for ranging with a FM-CW radar is (1)

$$R = \frac{|f_1 - f_2| c}{4 f_3 f_4}$$

where:

R = Range to target
c = Velocity of propagation
f_1 = Frequency transmitted
f_2 = Frequency received
f_3 = Modulation rate
f_4 = Maximum frequency deviation

$f_1 - f_2$ is the range difference frequency which appears in the IF of a homodyne radar.

Almost any type of modulation can be used in a homodyne radar as long as the difference frequency appears in the IF of the sensor. This is definitely true for a sensor which is not concerned with measuring range. However, if the sensor must perform a ranging function, there are limitations. Heretofore, in FM-CW homodyne systems for measuring range, a frequency modulation technique was used which required the determination of a range difference frequency using filters in the intermediate frequency (IF) channel to either (a) track the range difference frequency or (b) modify the modulation rate in order to maintain a constant range difference frequency.[2] Two modulation schemes were utilized, either a nonlinear FM[3] or a linear FM. The nonlinear FM would detect a harmonic of the beat frequency in the IF which was essentially not amplitude modulated by the target. This reduced the automatic gain control (AGC) and antenna isolation[4] requirements of the system but had a complicated range ambiguity function.

If the homodyne oscillator is modulated in a linear manner (sawtooth or triangle) the signal returned from a target will have a different frequency from that being transmitted. The radar receiver mixes the two frequencies and the average difference, the beat frequency, is a linear function of range as shown in the above equation. The beat frequency can be determined two ways. (1) The modulation rate can be held constant and the beat frequency can be tracked in the radar IF to determine the range or (2) the beat frequency can be tracked in the IF and the modulation rate changed to maintain a constant beat frequency. Method one monitors the IF tracking filter control voltage to infer range while method two monitors the control voltage of the modulation oscillator.

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[1] Skolnick, M. I., "Introduction to Radar Systems," pp. 86-90, McGraw Hill Book Co., New York, 1962.

[2] Ibid, pp. 94-95.

[3] Ibid, pp. 100-103.

[4] Ibid, pp. 75-77.

There are some major disadvantages with these methods when applied to small, simple systems.

a. Range accuracy is a function of the linearity of the VCO used and the range to the target.

b. The beat frequency must be measured and tracked in the IF in a linear closed-loop system.

c. Because of limitations in the amount of frequency deviation that can be obtained from a RF VCO, the measured difference frequency can be small. This means an antenna with a very low voltage-standing wave ratio (VSWR) must be used.

In order to eliminate the requirement to track in frequency, a square wave modulation is applied to the R.F. voltage controlled oscillator which serves as the transmitter/LO. This results in two distinct time-shared frequencies being generated whose difference is the I.F. frequency. The signal received by the radar is the transmitted signal delayed in time by the propagation path. The R.F. mixer output is the difference frequency of the transmitted signal and the delayed transmitted signal and appears as a series of pulses in the I.F. with duty factor proportional to range. At the video output there will appear a pulse train and thus the delay. By threshold detecting the video signal and passing the resultant pulse train through a low pass filter, a voltage is generated which is a linear function of range.

It can be seen that by measuring the duty factor of the output pulse train, we are essentially measuring the average difference frequency so that

$$\overline{f_1 - f_2} = Df_4 \quad \text{where} \quad D = \text{Duty factor} \tag{2}$$

The range equation then becomes

$$R = \frac{Dc}{4f_3} \tag{3}$$

The system accuracy is therefore no longer a function of the linearity of the VCO, and the requirement for an I.F. tracking filter has been removed.

The homodyne radar displayed in Figure 7 is of fairly standard design. However, due to the unique modulation scheme various components common to other systems are missing. The system operates as follows (referring to Figure 7). The crystal oscillator applies a TTL level square wave signal to the transmitter/LO modulator. The transmitter/LO is a voltage controlled oscillator whose output frequency is a function of an applied voltage. The modulator applies a square waveform of proper level to shift the output of the transmitter/LO between two frequencies ($f_0 + f_4$) whose difference (f_4) is the I.F. frequency. In this application an additional low signal (30 kHz) is added to the square so that the RF bandwidth is increased. Figure 8 is a

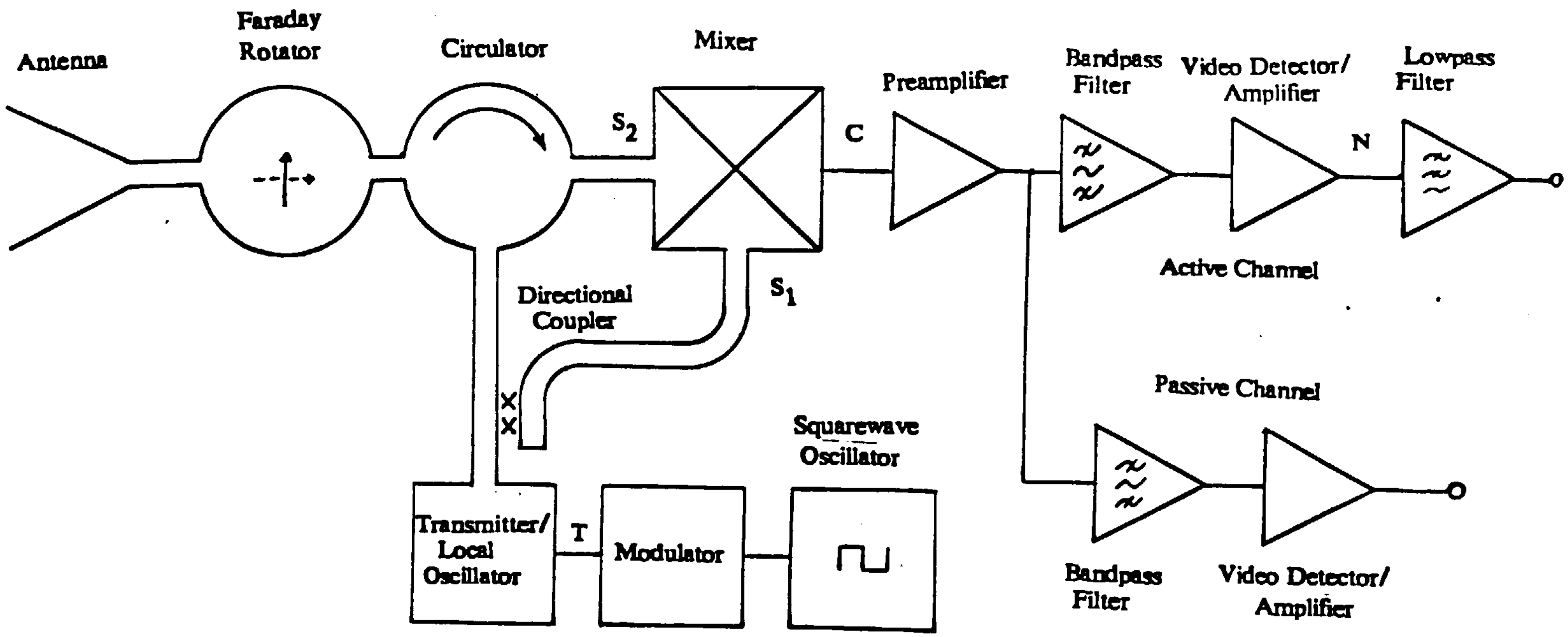


Figure 7. Frequency Modulated Homodyne Radar

photo of the RF spectrum. The broadness of the two portions of the spectrum are a function of the low frequency modulation, while the separation of the two portions is a function of the square waveform.

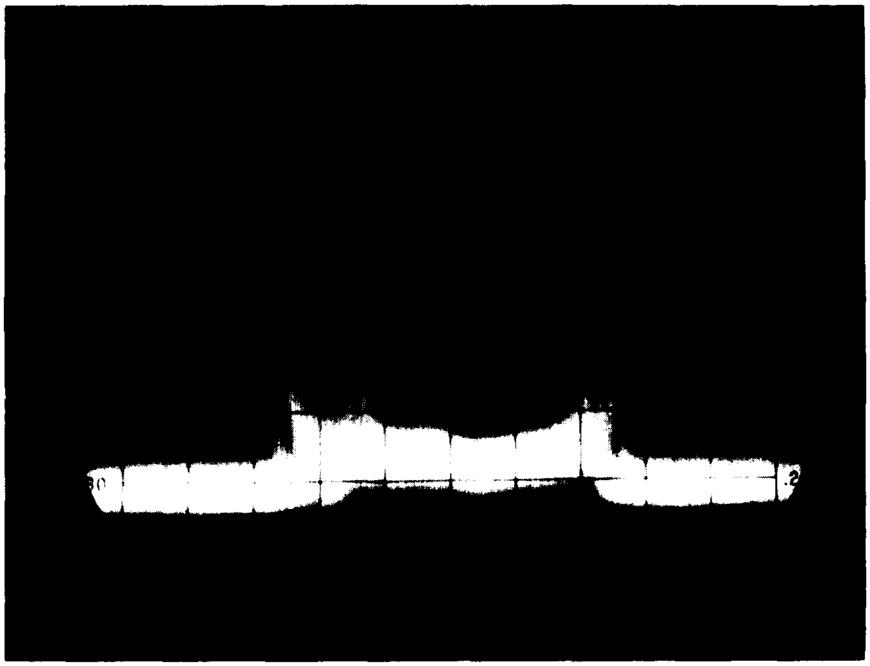


Figure 8. RF Spectrum with Square Wave Modulation

The output of the transmitter/LO is directed by the circulator out the antenna. A portion of the R.F. power generated, S_1, is supplied to the R.F. mixer by the directional coupler. The return signal, S_2, is delayed in time by the propagation time to and from the target of interest. The two signals S_2 and S_1, are mixed and the output, C, is the difference frequency, $S_1 - S_2$. The difference frequency passes through the I.F. preamplifier, through the narrow bandpass filter and is detected and amplified, N.

One salient feature of the system is the reduction in required video dynamic range when measuring backscatter. At short ranges, the backscattered peak power would be high for a given target but the duty cycle would be low, while at longer ranges the backscattered peak power would be low and the duty cycle high. Thus, at long ranges, out to the maximum unambiguous range, the system would be operating with an apparently higher average power than it would be at shorter range. This action results in the integrated output signal being inversely proportional to the third power of range instead of the fourth power, assuming a square-law detector and linear system. By using a logarithmic I.F. or video, the backscatter dependence on range can be further reduced.

Figure 9 is a conceptual design of a cross-polarized radar. The sensor shown in this figure uses an antenna which serves not only to generate orthogonal transmission and reception polarizations but also serves as a signal duplexer, replacing the circulator. The schematic shows two antennas

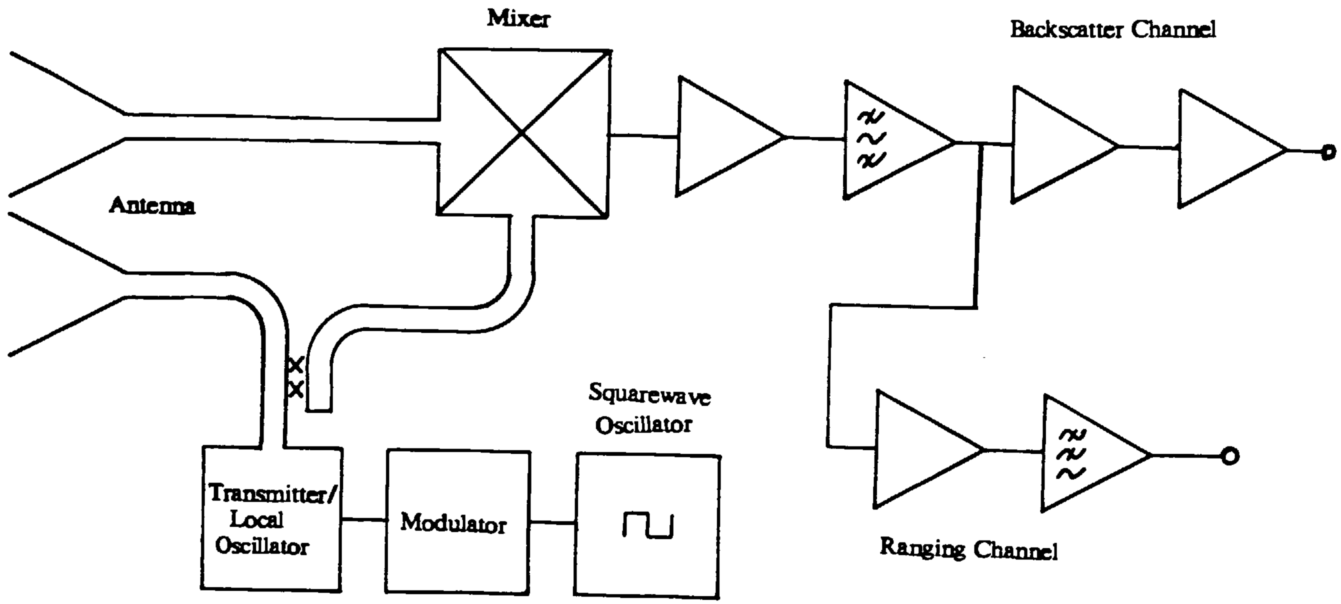


Figure 9. Conceptual Design Cross-Polarization Radar

side by side, but actually the two occupy the same aperture. The antenna will be a planner design which allows very inexpensive and highly automated production. The duplexing and orthogonal polarizations may be achieved by either feeding square radiating patches on the surface on orthogonal sides or feeding orthogonal arrays of radiators. The antenna will then have two separate ports with separate feed networks. The sensor, as envisioned, will operate at 60 GHz to reduce the susceptibility to countermeasures. The RF and IF components will operate in the same way as those in the sensor currently being tested. The entire sensor should be manufacturable in microstrip, increasing productivity and reliability and reducing costs.

III. CROSS-POLARIZED SADARM MEASUREMENTS

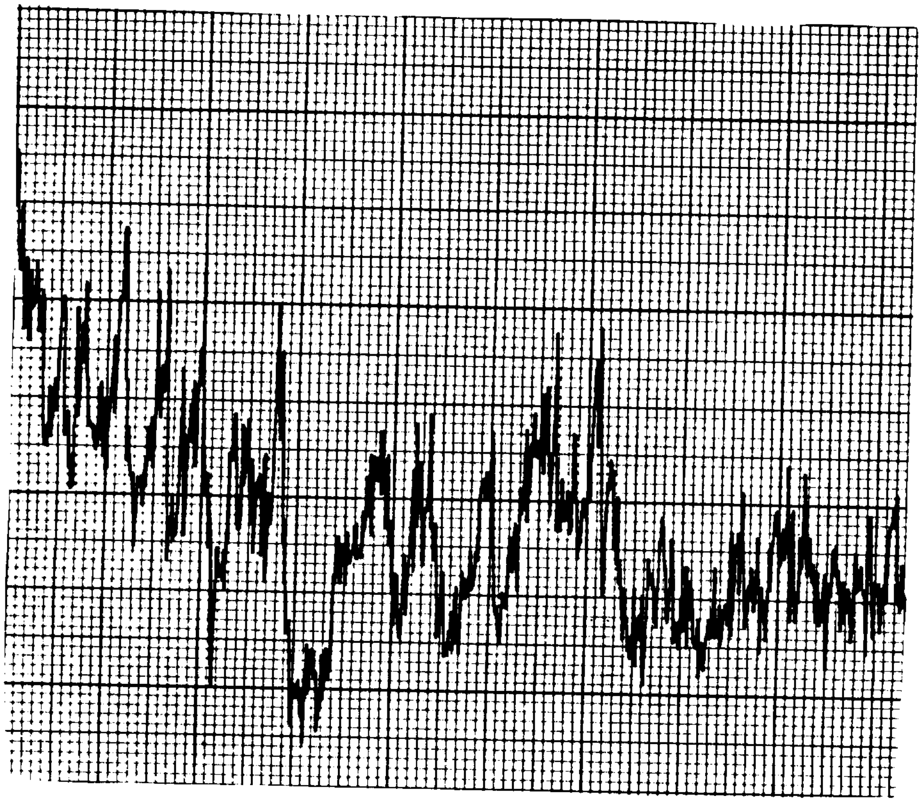
The first series of SADARM radar measurements **was** made at the US Air Force, North East Test Range, Stockbridge, New York. A 35 GHz multimode sensor capable of operation in either active or passive modes was mounted on an XM-21 gun mount located on the side of a UH-1M helicopter. Armored targets were measured at ranges of 30 to 150 meters at a fixed angle of 30 degrees off vertical. The sensor was capable of operation in either co-polarized modes or a cross-polarized mode, transmitting vertical polarization and receiving horizontal polarization. Measurements were recorded during the winter, with various amounts of snow cover, and during the summer.

Figure 10 shows the data from two successive flights over four armored vehicles. The reflections from the snow for the co-polarized radar were at a level such that the armored targets could not be detected. The normalized radar cross section of the snow measured as high as + 5 dB during the winter months. The average snow reflections for the cross-polarized radar were less, and all four armored targets were detected.

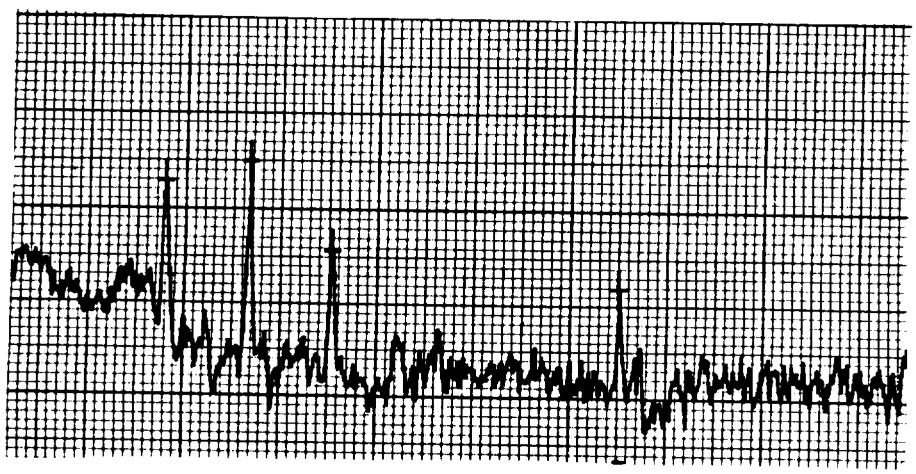
Figure 11 shows the data from two successive flights over five armored targets. These data were recorded during the summer tests at Stockbridge using the same multimode sensor. The cross-polarized radar shows a marked improvement in the target signal-to-background clutter ratio over the co-polarized radar. These and other radar data recorded during the winter and summer months at Stockbridge indicated that the concept of cross-polarization should be further investigated.

The multimode sensor used in the Stockbridge tests was replaced with a new multifrequency-multimode sensor designed and fabricated at BRL. This system was capable of simultaneous co-polarization and cross-polarization measurements, at both 35 GHz and 95 GHz. Both radars had six-inch antennas that were boresighted together. Figure 12 shows the data from all the sensor outputs for a pass over three armored targets and 1,000 meters of background. The measured target to clutter ratio was greater for both cross-polarized radars than for the co-polarized radars. This multifrequency sensor was used to measure various targets and backgrounds at ranges of 30 to 200 meters. Both radars responded to targets and backgrounds alike, the only difference being the antenna resolution.

Figure 13 shows the data for a flight over three armored targets and 1,500 meters of background. The first pulse, where no target is shown, is a 2-1/2 ton truck. The small double pulse halfway between the truck and first

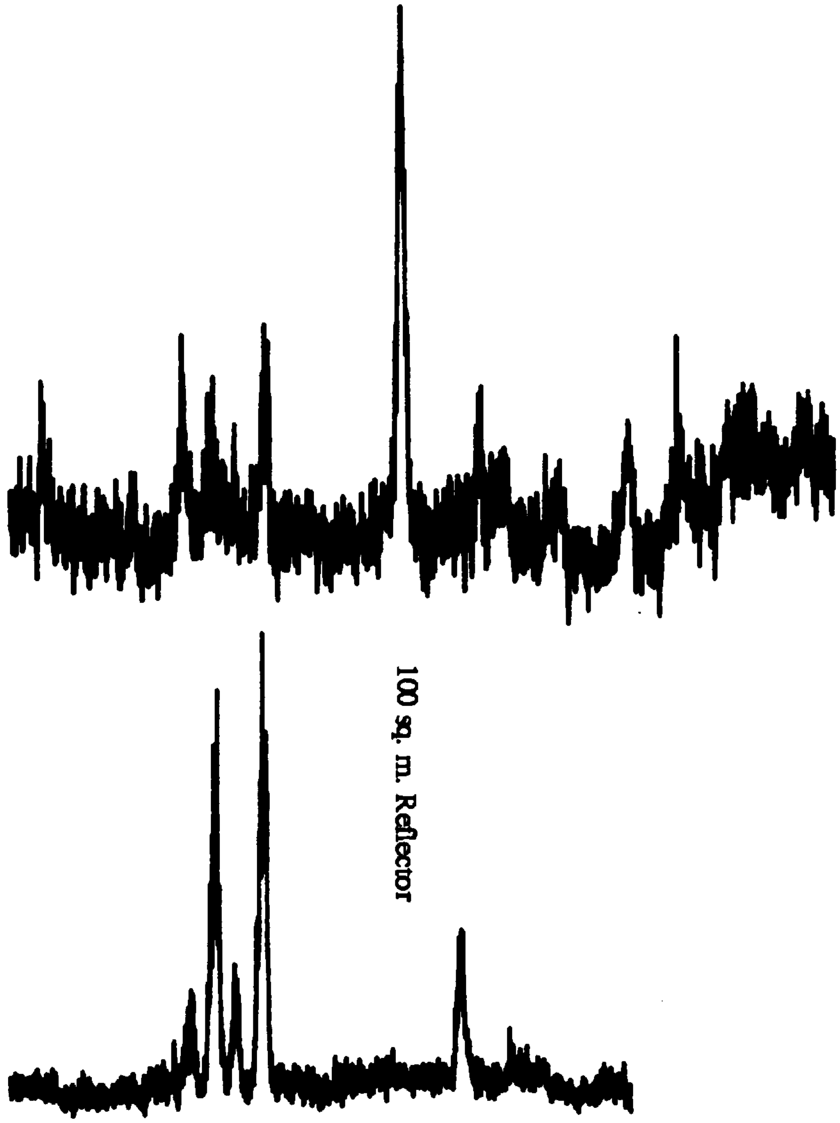


A Sensor Output (Transmit and Receive Vertical Polarization). Winter Data. Range to Ground = 90m.



B Sensor Output (Transmit Vertical/Receive Horizontal Polarization). Winter data. Range to Ground = 50m.

Figure 10. Winter Radar Measurements Stockbridge Test Site



Comparison of Sensors: Transmit and Receive Vertical Polarization (Top) vs. Transmit Vertical/Receive Horizontal Polarization (Bottom). Summer Data. Range to Ground = 150m.

Figure 11. Summer Radar Measurements Stockbridge Test Site

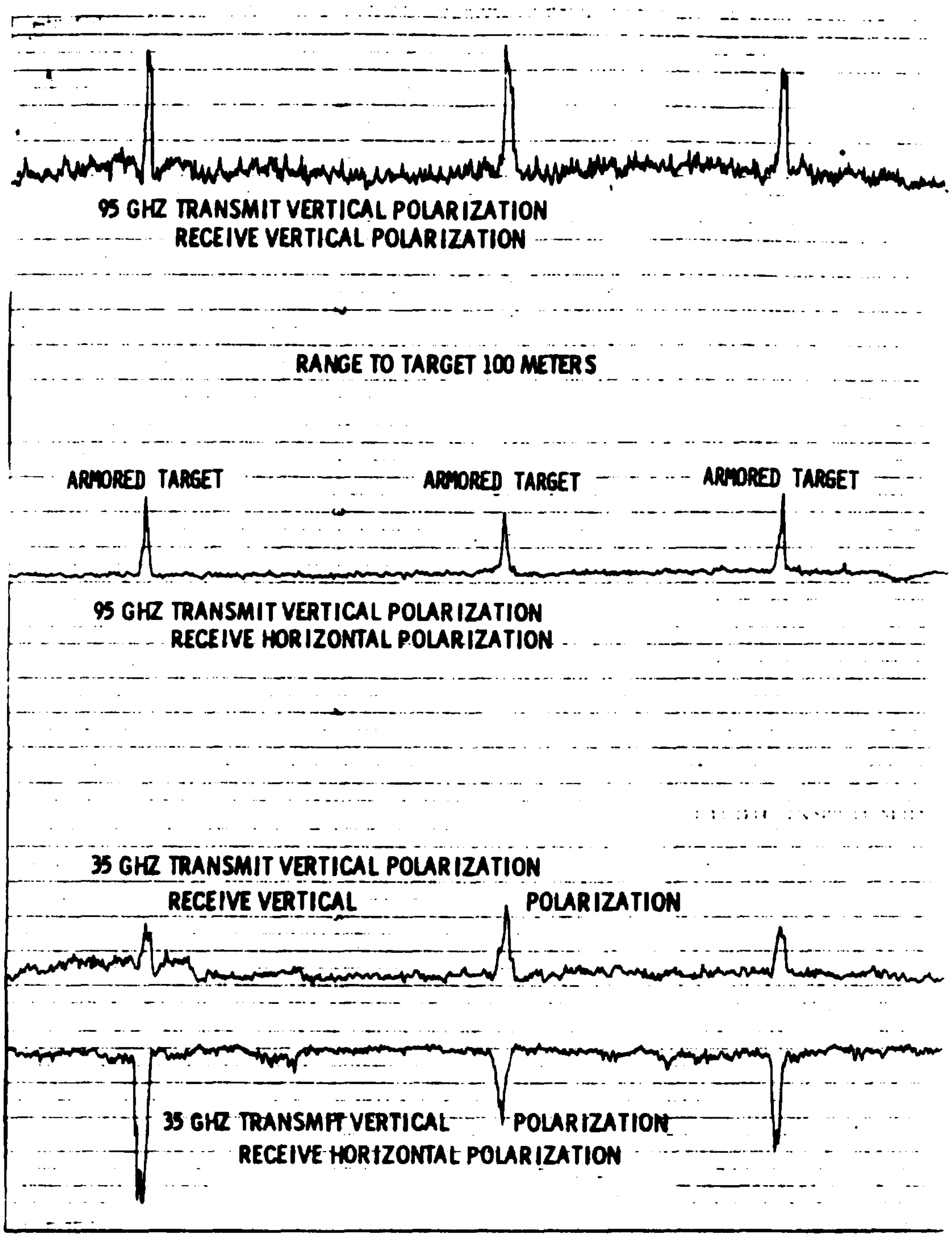


Figure 12. Multifrequency Radar Measurements

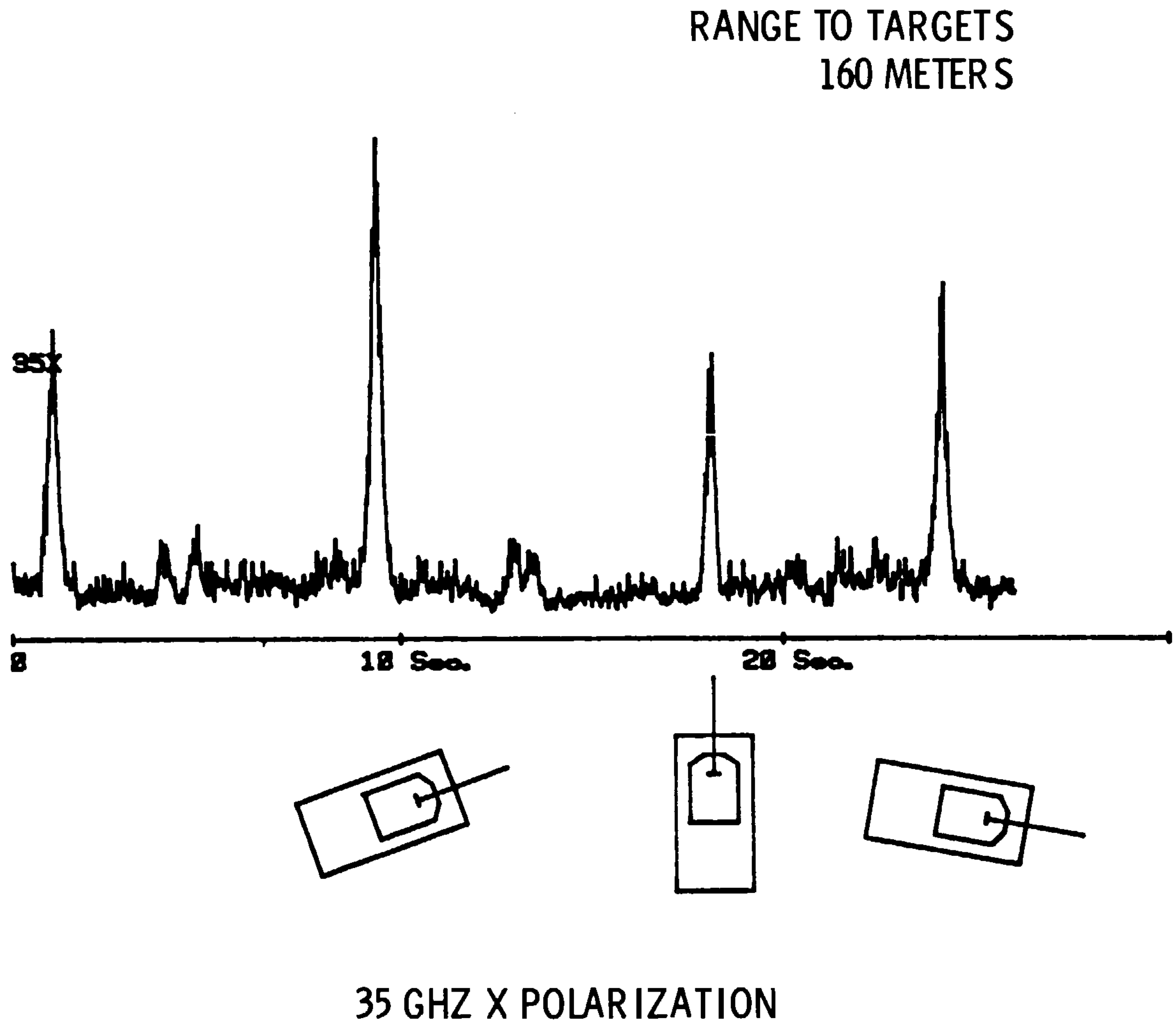


Figure 13. Target Signals 35 GHz Cross-Polarization

target is a double rail, similar to a railroad, but spaced 4 meters apart. The double pulse between the first and second tank is a tidal creek, approximately 3 meters wide. This area is very muddy and the banks on both sides of the creek appear to have a cross-polarized response. Subsequent measurements of other tidal mud flats and marsh areas also showed some cross-polarized signal return. Most of the background covered in this 1,500-meter sweep was short grass and weeds. Some tree rows and two dirt roads were also within the measured flight path.

In both the SADARM and STAFF applications, the sensor must be capable of initiating a trigger pulse when the self-forging fragment is pointed at a vulnerable part of an armored target. For top-attack systems the vulnerable part of an armored target is an area near the center of the vehicle that extends from the front driver's compartment to the engine compartment behind the turret. The sensor must then determine the center of the target, then direct fire at this point. The radiometric sensor used in the previous SADARM and STAFF demonstration programs performed this task by setting a threshold level above background and sensor noise, measuring the width of the target pulse at this level, and then dividing the target pulse width in half. This type of signal processing requires that the sensor antenna beam lead the warhead lethal axis by some fixed angle. The detonation trigger pulse delay time is then a function of this lead angle and the submunition spin rate.

A radar target, in particular an armored vehicle, is made up of a large number of scattering and reflecting surfaces and corner reflectors. If the radar sensor antenna beam width, on the ground, is comparable to or smaller than the target, then the larger reflecting points may be spaced in a nonuniform manner across the portion of the target the antenna beam has passed over. This causes an amplitude shift in the target pulse which imparts an aim point error to the munition. When the antenna beam width on the ground is larger than the target, all the reflecting elements are integrated into a single more uniform target pulse. At longer ranges the aim point shifts back toward the center of the target.

Figure 14 shows the cross-polarized radar data from a flight over two armored targets at a range of 150 meters. IRIG time was recorded on both analog and video data tapes, so that each target pulse and the accompanying television pictures could be analyzed for aim point accuracy. The tank diagrams with the arrows, shown below each pulse, indicate how the antenna beam passed over the target. The cross on the arrow indicates where the measured center of the pulse is located. This would be the warhead aim point on the target.

IV. STAFF CROSS-POLARIZED RADAR DATA

The sensor used in a STAFF weapon system concept must measure the projectile spin rate, detect the target, and then direct fire to a vulnerable part of that target. The self-forging fragment warhead in the STAFF projectile is offset 90 degrees relative to the sensor antenna boresight. The aim point accuracy will be a function of the sensor's ability to measure spin rate and measure the center of the target. The radiometric sensor used in the STAFF demonstration performed both of these tasks admirably, in that the munition hit the center of an armored target.

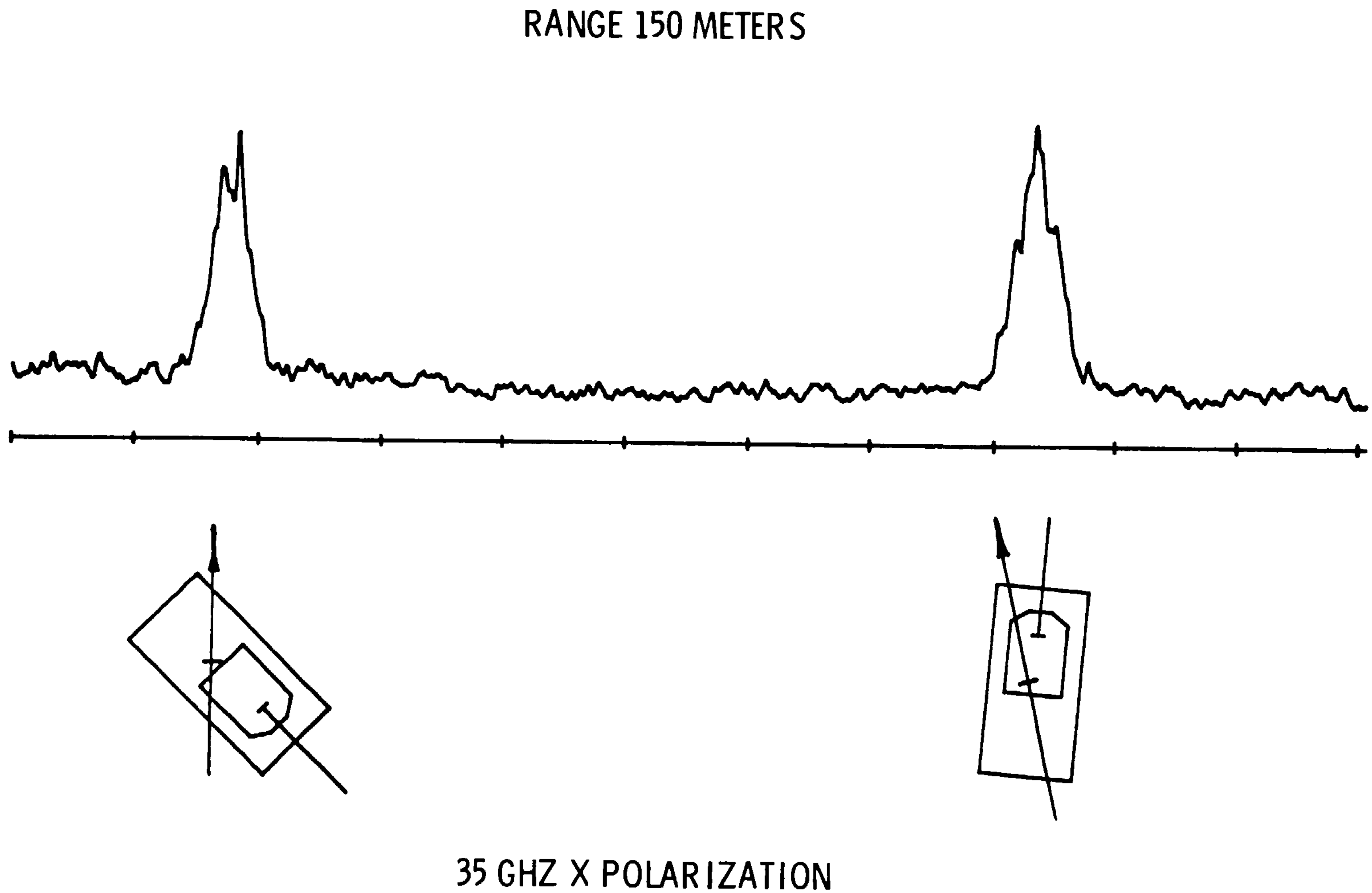


Figure 14. Pointing Errors 35 GHz Cross-Polarization

The STAFF sensor antenna is pitched forward 7 degrees relative to the plane of the projectile; however, when the system is fired at distant target the projectile can pitch forward as much as 7 degrees when it passes over the target. The antenna beam will then sweep through a zero degree grazing angle; that is the sensor may be required to look directly at the ground. A co-polarized radar could experience a change in ground reflected signals of as much as 50 dB as the antenna beam swept through one 360 degree revolution.

A 35 GHz cross-polarized radar/radiometer was mounted on top of a 30 meter portable tower in such a way that it could be swept through a scan similar to the zero degree pitch angle scan of the STAFF sensor. Figure 15 shows the data for a single scan across a mud and grass background. A 0.6 square meter calibrated dihedral reflector was situated directly beneath the sensor at zero degrees. The background was short grass with muddy areas where tank treads had plowed up the ground. The peak variations in background radar cross section are 0.1 square meter or less, and are due to orthogonally polarized reflections from the muddy tank tracks. The variations noted in the scan are signals reflected from individual components of the background. The average signal output of the radar does not change as it sweeps from horizon to horizon through zero degree pitch and scan angles. A similar sweep was made over an asphalt road. There was no discernable signal out of the radar until the antenna beam began to see the edges of the road, then the signals were less tan 0.1 square meter.

Figure 16 shows data from a single sweep across the background with an armored target and a calibrated dihedral reflector located on either side of the scan. The target figure, with the arrow, shows where the antenna beam crossed the target. The range of these targets was approximately 33 meters. The background variations located between 0 and 10 degrees in the sweep are muddy tank tracks. The radiometric scan of the target shown as a dashed pattern, is useful in analyzing the radar signal. In this scan the radar signal reflected off the tank was uniform except for a power variation in the signal level above 5 square meters. A measure of the radar pulse width and division at a threshold level above the background noise would produce a trigger pulse at the same time as the trigger pulse generated by the radiometer. Subsequent measurements of the target at different positions within the antenna sweep did not show this close relationship in aim point accuracy. There was usually a bias toward one side of the target.

The optimum antenna beamwidth for the STAFF system would be about 15 degrees. Those measurements were made with a 4.7 deg beamwidth antenna and show the effect of target breakup and aimpoint bias when the target is larger than the beamprint.

V. CONCLUSIONS

Information has been presented which demonstrates the feasibility of using cross-polarized radars to improve the signal-to-clutter ration for top-attack weapon systems. It has been shown to be feasible for both SADARM and STAFF type systems which are required to locate armored targets in clutter at steep depression angles.

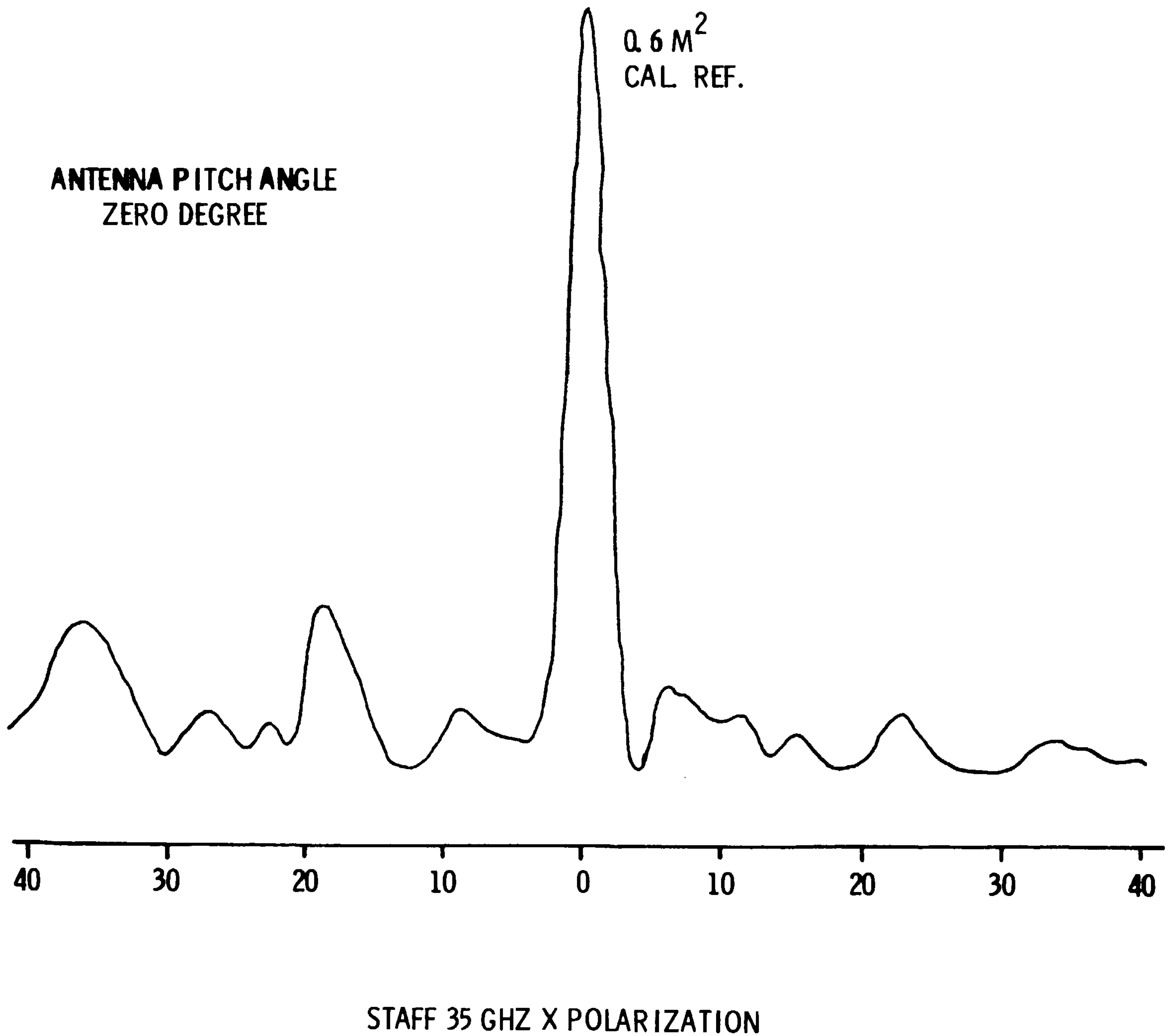
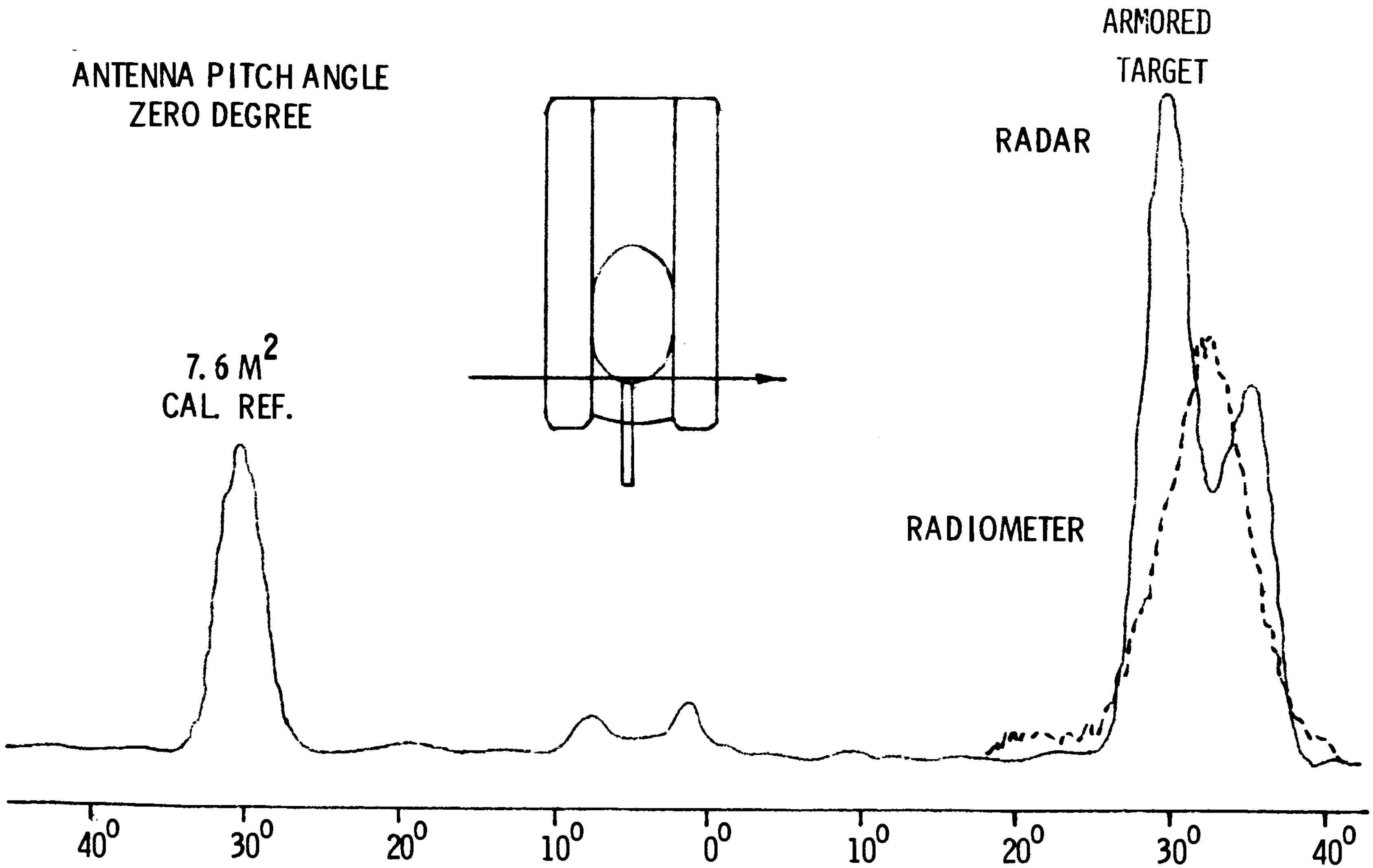


Figure 15. Staff 35 GHz Zero Angle Scan Cross-Polarization



STAFF 35 GHZ X POLARIZATION

Figure 16. Staff 35 GHz Target Background Scan

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